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14. ABSTRACT

GPS-denied indoor mobile mapping has been an active area of research for many years. With applications such as historical preservation, entertainment, and augmented reality, the demand for both fast and accurate scanning technologies has dramatically increased. In this project, we developed two algorithmic pipelines for GPS-denied indoor mobile 3D mapping using an ambulatory backpack system. By mounting scanning equipment on a backpack system, a human operator can traverse the interior of a building to produce a high-quality 3D reconstruction. In

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UU	UU	UU	UU		19b. TELEPHONE NUMBER 510-643-6777

Report Title

Final Report: Fast, Automated, Photo-realistic, 3D Modeling of Building Interiors (ATTN: Modeling of Complex Systems Program, Manager John Lavery)

ABSTRACT

GPS-denied indoor mobile mapping has been an active area of research for many years. With applications such as historical preservation, entertainment, and augmented reality, the demand for both fast and accurate scanning technologies has dramatically increased. In this project, we developed two algorithmic pipelines for GPS-denied indoor mobile 3D mapping using an ambulatory backpack system. By mounting scanning equipment on a backpack system, a human operator can traverse the interior of a building to produce a high-quality 3D reconstruction. In each of our presented algorithmic pipelines, data from a number of 2D laser scanners, a camera, and an IMU is fused together to track the 3D position of the system as the operator traverses an unknown environment. This project presents a number of novel contributions f or indoor GPS-denied 2.5 and 3D mobile mapping using a number of 2D laser scanners, a camera, and an IMU. First, for 3D mapping we develop a tightly coupled EKF estimator for fusing data from all sensors into a single optimized 3D trajectory. By formulating each sensor's contributions independently, we demonstrate a modular algorithm that easily scales to an arbitrary number of 2D laser scanners. In contrast to existing work that either assumes a known fixed map or limits the environment to a set of axis aligned planes, we demonstrate the ability to map environments containing horizontal and vertical planes of arbitrary orientation with no a priori information. Additionally, through timing and complexity analysis, we demonstrate that the runtime of the proposed EKF estimator is only linear in the acquisition time. Secondly, by including in our EKF estimator the laser scanner's spatial and temporal calibration parameters, we present a novel laser calibration methodology. Through simulated and real-world data, we validate that the proposed algorithms are capable of calibrating both the extrinsic and temporal misalignments present in our system's laser data. Lastly, we address the scalability of the proposed approach by utilizing a graph optimization post processing step that overcomes any accumulated drift in the EKF estimator. We then validate the proposed 3D end-to-end localization system using 3 multi-story datasets collected from real-world environments. The system's reconstructions are compared against CAD drawings of the buildings and are shown to achieve an intersection over union of over 96% on all datasets. Lastly, we demonstrate accuracy improvements over our 2.5D methods using a comparison test against data collected with a static scanner. In addition to 3D mapping, we also present a methodology for 2.5D mapping with three novel contributions. First, we present a method for automatically segmenting barometric pressure data based on the floor of the building it was collected from. Specifically, by using Bayesian non-parametrics we are able to demonstrate simultaneous floor detection and the corresponding data segmentation. The data segmentation is then used to extend classical 2D particle filtering across any number of discrete building stories. Secondly, we demonstrate a genetic scan matching algorithm used to estimate loop closure constraints even without an accurate initial condition. Through simulation and real-world experiments we show an improvement over state of the art scan matching techniques. Next, we present two metrics that are used to validate the results of the genetic scan matching algorithm. We use both a correlation and shape metric to demonstrate robust and accurate validation of loop closure constraints in indoor environments. Lastly, we compare and characterize the performance of the proposed 3D and 2.5D mapping techniques developed in this project. Although the 2.5D mapping techniques are more computationally lightweight, we show that the accuracy of system is significantly improved using the 3D mapping algorithm.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Keynote speaker for VCIP (visual communication and image processing) Conference, November 2012, San Diego, "Fast Automated 3D Modeling of Indoor Environments"
Keynote speaker for ICME (International Conference on Multimedia Exposition), July, 2011, Barcelona, Spain
Invited presentation at SPIE Electronic Imaging Conference on Image Based Localization, February 2016, San Francisco, CA
Invited talk at SPAR International, Coloroda Springs on 3D modeling of indoor environments, April 16th , 2014. ? Invited talk at Center for Built Environment, Berkeley CA on 3D modeling of indoor environments with applications to building energy efficiency, April 24, 2014.

Number of Presentations: 4.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Best paper award for the paper
R. Garcia and A. Zakhor, "Markerless motion capture with multi-view structured light", SPIE Electronic imaging conference on 3D Image Processing, Februay 2016, San Francisco, CA

Graduate Students

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Post Doctorates

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Faculty Supported

NAME PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Names of Under Graduate students supported

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FTE Equivalent:
Total Number:

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

<u>NAME</u>

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Technology Transfer

Final Report for ARO Grant W911NF-11-10088
P.I. Avideh Zakhor, U.C. Berkeley

I. ABSTRACT

GPS-denied indoor mobile mapping has been an active area of research for many years. With applications such as historical preservation, entertainment, and augmented reality, the demand for both fast and accurate scanning technologies has dramatically increased. In this project, we developed two algorithmic pipelines for GPS-denied indoor mobile 3D mapping using an ambulatory backpack system. By mounting scanning equipment on a backpack system, a human operator can traverse the interior of a building to produce a high-quality 3D reconstruction. In each of our presented algorithmic pipelines, data from a number of 2D laser scanners, a camera, and an IMU is fused together to track the 3D position of the system as the operator traverses an unknown environment. This project presents a number of novel contributions f or indoor GPS-denied 2.5 and 3D mobile mapping using a number of 2D laser scanners, a camera, and an IMU. First, for 3D mapping we develop a tightly coupled EKF estimator for fusing data from all sensors into a single optimized 3D trajectory. By formulating each sensor's contributions independently, we demonstrate a modular algorithm that easily scales to an arbitrary number of 2D laser scanners. In contrast to existing work that either assumes a known fixed map or limits the environment to a set of axis aligned planes, we demonstrate the ability to map environments containing horizontal and vertical planes of arbitrary orientation with no a priori information. Additionally, through timing and complexity analysis, we demonstrate that the runtime of the proposed EKF estimator is only linear in the acquisition time. Secondly, by including in our EKF estimator the laser scanner's spatial and temporal calibration parameters, we present a novel laser calibration methodology. Through simulated and real-world data, we validate that the proposed algorithms are capable of calibrating both the extrinsic and temporal misalignments present in our system's laser data. Lastly, we address the scalability of the proposed approach by utilizing a graph optimization post processing step that overcomes any accumulated drift in the EKF estimator. We then validate the proposed 3D end-to-end localization system using 3 multi-story datasets collected from real-world environments. The system's reconstructions are compared against CAD drawings of the buildings and are shown to achieve an intersection over union of over 96% on all datasets. Lastly, we demonstrate accuracy improvements over our 2.5D methods using a comparison test against data collected with a static scanner. In addition to 3D mapping, we also present a methodology for 2.5D mapping with three novel contributions. First, we present a method for automatically segmenting barometric pressure data based on the floor of the building it was collected from. Specifically, by using Bayesian non-parametrics we are able to demonstrate simultaneous floor detection and the corresponding data segmentation. The data segmentation is then used to extend classical 2D particle filtering across any number of discrete building stories. Secondly, we demonstrate a genetic scan matching algorithm used to estimate loop closure constraints even without an accurate initial condition. Through simulation and real-world experiments we show an improvement over state of the art scan matching techniques. Next, we present two metrics that are used to validate the results of the genetic scan matching algorithm. We use both a correlation and shape metric to demonstrate robust and accurate validation of loop closure constraints in indoor environments. Lastly, we compare and

characterize the performance of the proposed 3D and 2.5D mapping techniques developed in this project. Although the 2.5D mapping techniques are more computationally lightweight, we show that the accuracy of system is significantly improved using the 3D mapping algorithm.

II. Peer reviewed Conference Proceedings

[1] E. Turner and A. Zakhor, **"Automatic Indoor 3D Surface Reconstruction with Segmented Building and Object Elements"** International Conference on 3D Vision, Lyon, France, October 2015. [Adobe PDF]

[2] R. Zhang and A. Zakhor, **"Automatic Identification of Window Regions on Indoor Point Clouds Using Lasers and Cameras,"** submitted to IEEE Winter Conference on Applications of Computer Vision, Steamboat Springs CO., March 24-26, 2014. [Adobe PDF]

[3] E. Turner, and A. Zakhor, **"Floor plan Generation and Room Labeling of Indoor Environments from Laser Range Data,"** submitted to GRAPP 2014, Lisbon, Portugal, January 2014. [Adobe PDF]

[4] E. Turner and A. Zakhor, **"Watertight Planar Surface Meshing of Indoor Point-Clouds with Voxel Carving,"** submitted to 3DV 2013. Seatle, Washington, June 2013. [Adobe PDF]

[5] N. Corso and A. Zakhor, **"Loop Closure Transformation Estimation and Verification Using 2D LiDAR Scanners,"**submitted to special issue on mobile laser scanning and mapping, Journal of Remote Sensing, August 2013 [Adobe PDF]

[6] P. Cheng, M. Anderson, S. He, and A. Zakhor, **"Texture Mapping 3D Planar Models of Indoor Environments with Noisy Camera Poses,"** SPIE Electronic Imaging Conference, Multimedia Content Access. Burlingame, California, February 2013.[Adobe PDF]

[7] R. Garcia and A. Zakhor, **"Geometric Calibration for a Multi-Camera-Projector System,"** IEEE Workshop on the Applications of Computer Vision (WACV) 2013. Clearwater Beach, Florida, January 2013. [Adobe PDF]

[8] E. Turner and A. Zakhor, **"Watertight As-Built Architectural Floor Plans Generated from Laser Range Data,"** 3DIMPVT, October 2012, Zurich, Switzerland. [Adobe PDF]

[9] E. Turner and A. Zakhor, **"Sharp Geometry Reconstruction of Building Facades Using Range Data,"** International Conference on Image Processing, Orlando, Florida, Sep. 2012. [Adobe PDF]

[10] V. Sanchez and A. Zakhor, **"Planar 3D Modeling of Building Interiors from Point Cloud Data,"** International Conference on Image Processing, Orlando, Florida, Sep. 2012. [Adobe PDF]

[11] S. Lagüela, J. Arnesto, P. Arias, and A. Zakhor, **"Automatic Procedure for the Registration of thermographic Images with Point Clouds,"** International Society for Photogrammetry and Remote Sensing (ISPRS), Melbourne, Australia, 2012.[Adobe PDF]

[12] J. Kua, N. Corso, A. Zakhor, **"Automatic Loop Closure Detection Using Multiple Cameras for 3D Indoor Localization,"**IS&T/SPIE Electronic Imaging 2012, Burlingame, California, January 22-26, 2012. [Adobe PDF]

[13] X. Shi and A. Zakhor, **"Fast Approximation for Geometric Classification of Lidar Returns,"** ICIP 2011, Brussels, Belgium, September 11-14, 2011. [Adobe PDF]

[14] N. Kawai and A. Zakhor, T. Sato, N. Yokoya, **"Surface Completion of Shape and Texture Based on Energy Minimization,"**ICIP 2011, Brussels, Belgium, September 11-14, 2011. [Adobe PDF]

III. Peer reviewed Journal publications

1. R. Garcia and A. Zakhor, **"Markerless Motion Capture with Multi-view Structured Light,"** submitted to *IEEE Transactions on Visualization and Computer Graphics*, January 2015, [Adobe PDF]
2. E. Turner, P. Cheng, and A. Zakhor, **"Fast, Automated, Scalable Generation of Textured 3D Models of Indoor Environments,"** *IEEE Journal on Selected Topics in Signal Processing*, Volume 9, No. 3, pp. 409-421, April 2015, [Adobe PDF]
3. N. Corso and A. Zakhor, **"Indoor Localization Algorithms for an Ambulatory Human Operated 3D Mobile Mapping System,"** *Remote Sensing 2013*, vol. 5, no. 12, pp. 6611-6646, Oct. 2013, [Adobe PDF]
4. R. Garcia and A. Zakhor, **"Consistent Stereo-Assisted Absolute Phase Unwrapping Methods for Structured Light Systems,"** *IEEE Journal on Selected Topics in Signal Processing*, vol. 6, no. 5, pp. 411-424, Sept. 2012, [Adobe PDF]

IV. In the news

October 29, 2015 - KQED: "Mapping Your World with a Backpack"

KQED feature on the 3D mapping project

June 8, 2015 - Berkeley Engineering: "The Mapping Backpack"

Berkeley engineering discuss our energy audit research.

June 4, 2015 - BBC Arabic: "Backpack Device Performs Three-Dimensional Scanning for any Building Design"

Our lab was visited by BBC Arabic to look at our backpack scanning system.

February 26, 2015 - Voice of America: "New Tool Maps Buildings' Energy Efficiency"

Voice of America shows off our latest backpack hardware at the ARPA-E summit.

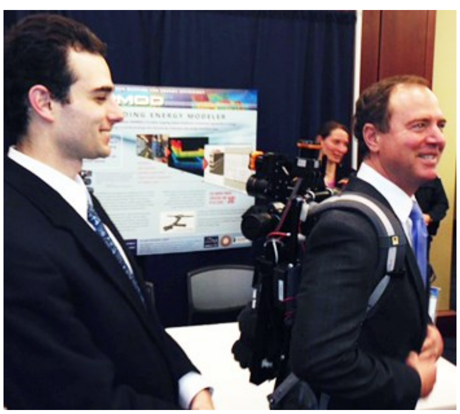
February 12, 2015 - BERC: "Berkeley Based Startups Win Big at ARPA-E"

Indoor Reality was among three winners of a start-up pitch competition to a panel of four investors.

February 11, 2015 - Avideh Zakhor Featured in ARPA-E Inspiring Innovators Showcase

November 13, 2014 - SWARM Lab Seminar: "Professor Zakhor's talk on image based localization"

February 28, 2014 - U.C. Berkeley NewsCenter: "Berkeley Team Takes its Energy Innovation to Capitol Hill"



A public affairs story of our visit to a Capitol Tech Showcase, held by ARPA-E.

February 26, 2014 - Energy Manager Today: Backpack Creates Thermal Maps

Energy Manager today ran a story about our latest backpack system.

February 26, 2014 - KTVU News Segment on 3D Mapping Backpack

The Channel 2 News ran a segment for our indoor modeling project.

February 26, 2014 - EnergyWire: "All-Seeing Backpack Homes in on Energy Waste"

EnergyWire article by David Ferris, E&E reporter

February 25, 2014 - LBNL Newsletter on RAPMOD at ARPA-E Tech Showcase

Lawrence Berkeley Lab's monthly newsletter showcased us presenting our latest hardware for our indoor modeling project.

December 10, 2013 - FierceWirelessTech: "UC Berkeley Pursues Indoor Positioning Via Smartphone Photos"

This article showcases our research in positioning systems using just smartphone cameras.

August 29, 2012 - A Backpack for BIM

GeoDataPoint report by Christine Grahl

V. PRESENTATIONS

- Keynote speaker for VCIP (visual communication and image processing) Conference, November 2012, San Diego, "Fast Automated 3D Modeling of Indoor Environments"
- Keynote speaker for ICME (International Conference on Multimedia Exposition), July, 2011, Barcelona, Spain
- Invited presentation at SPIE Electronic Imaging Conference on Image Based Localization, February 2016, San Francisco, CA
- Invited talk at SPAR International, Coloroda Springs on 3D modeling of indoor environments, April 16th , 2014. • Invited talk at Center for Built Environment, Berkeley CA on 3D modeling of indoor environments with applications to building energy efficiency, April 24, 2014.

VI. HONORS AND AWARDS

Best paper award for the paper
R. Garcia and A. Zakhor, "Markerless motion capture with multi-view structured light", SPIE Electronic imaging conference on 3D Image Processing, Februay 2016, San Francisco, CA

VII. PATENTS AWARDED

VIII. PERSONNEL SUPPORTED

Avideh Zakhor, Professor
Nicholas Corso, Graduate student
Eric Turner, Graduate student
John Kua, Staff member
Richard Zhang, Graduate Student
Victor Sanchez, Postdoc
Ricardo Garcia, Graduate Student
Peter Cheng, Graduate Student
Plamen Levchev, Staff Member
N. Kawai, Postdoc

IX. Graduating Undergraduate Metrics

- Eric Liang currently graduate student in computer science at CMU
- Jason Liang currently graduate student in ECE at University of Texas, Austin
- Gurshamnjot Singh currently working at Intel
- David Zhang, currently working at Apple
- Vaishaal Shenkar, currently graduate student in computer science at UC Berkeley
- Mark Jouppi currently working at Goolge
- Chaoran Yu, currently working at Bloomberg
- Andrew Zhai currently working at Pinterest
- Eric Tzeng, currently graduate student at UC Berkeley
- Christopher Dinh, graduating May 2017 from UC Berkeley
- Raphael Townshend, currently a graduate student at Stanford

X. Master's Degrees Awarded

1 E. Turner, "**Watertight Floor Plans Generated from Laser Range Data,**" Master's Project, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, May 2013. [Adobe PDF]
2 N. Corso, "**Loop Closure Transformation Estimation and Verification Using 2D LiDAR Scanners,**" Master's Project, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, May 2013. [Adobe PDF]
3 P. Cheng, **"Texture Mapping 3D Models of Indoor Enviornments with Noisy Camera Poses,"** Master's Thesis, Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, December 2013.

XI. Scientific Progress and Accomplishments

1.1 Automatic Indoor 3D Surface Reconstruction with Segmented Building and Object Elements

Automatic generation of 3D indoor building models is important for applications in augmented and virtual reality, indoor navigation, and building simulation software. This paper presents a method to generate high-detail watertight models from laser range data taken by an ambulatory scanning device. Our approach can be used to segment the permanent structure of the building from the objects within the building. We use distinct techniques to mesh the building structure and the objects to efficiently represent large planar surfaces, such as walls and floors, while still preserving the fine detail of segmented objects, such as furniture or light fixtures. Our approach is scalable enough to be applied on large models composed of several dozen rooms, spanning over 14,000 square feet. We experimentally verify this method on several datasets from diverse building environments.

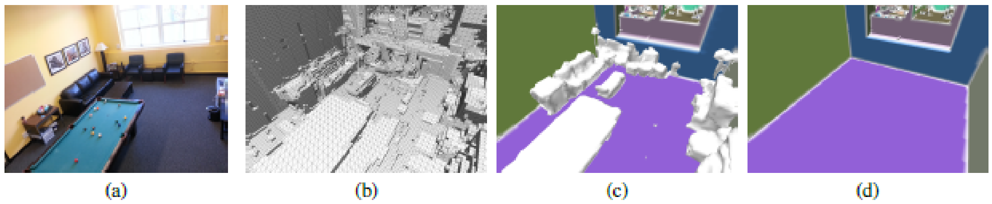


Figure 1: An area modeled by our technique: (a) a photo of the room; (b) the volumetric boundary of room; (c) final mesh with room and objects modeled; (d) final mesh of room only, colored by planar region.

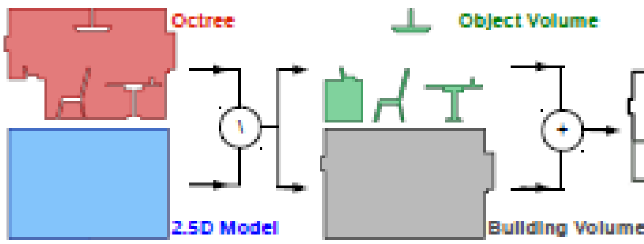


Figure 2: The scanned volume is meshed using two approaches that are combined to separate room geometry and object geometry. The complex geometry from the octree (upper left, in red) and the simple geometry from the 2.5D model (lower left, in blue) are combined to extract the object volume (upper center, in green) and the building volume (lower center, in grey). These volumes are meshed separately and exported (right, in black).

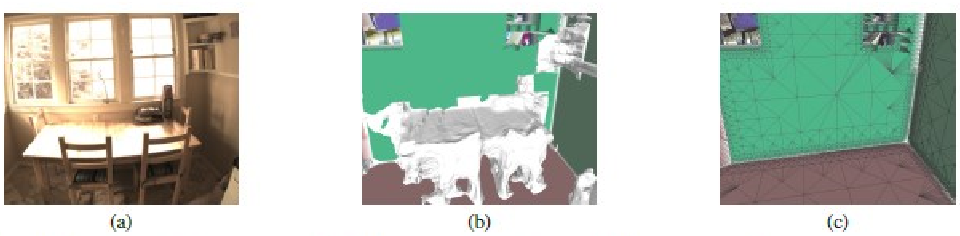
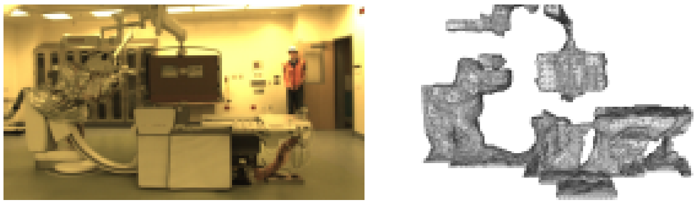


Figure 7: Example meshing output of residential area: (a) photo of area; (b) all reconstructed geometry; (c) geometry of room surfaces only, colored by planar region.



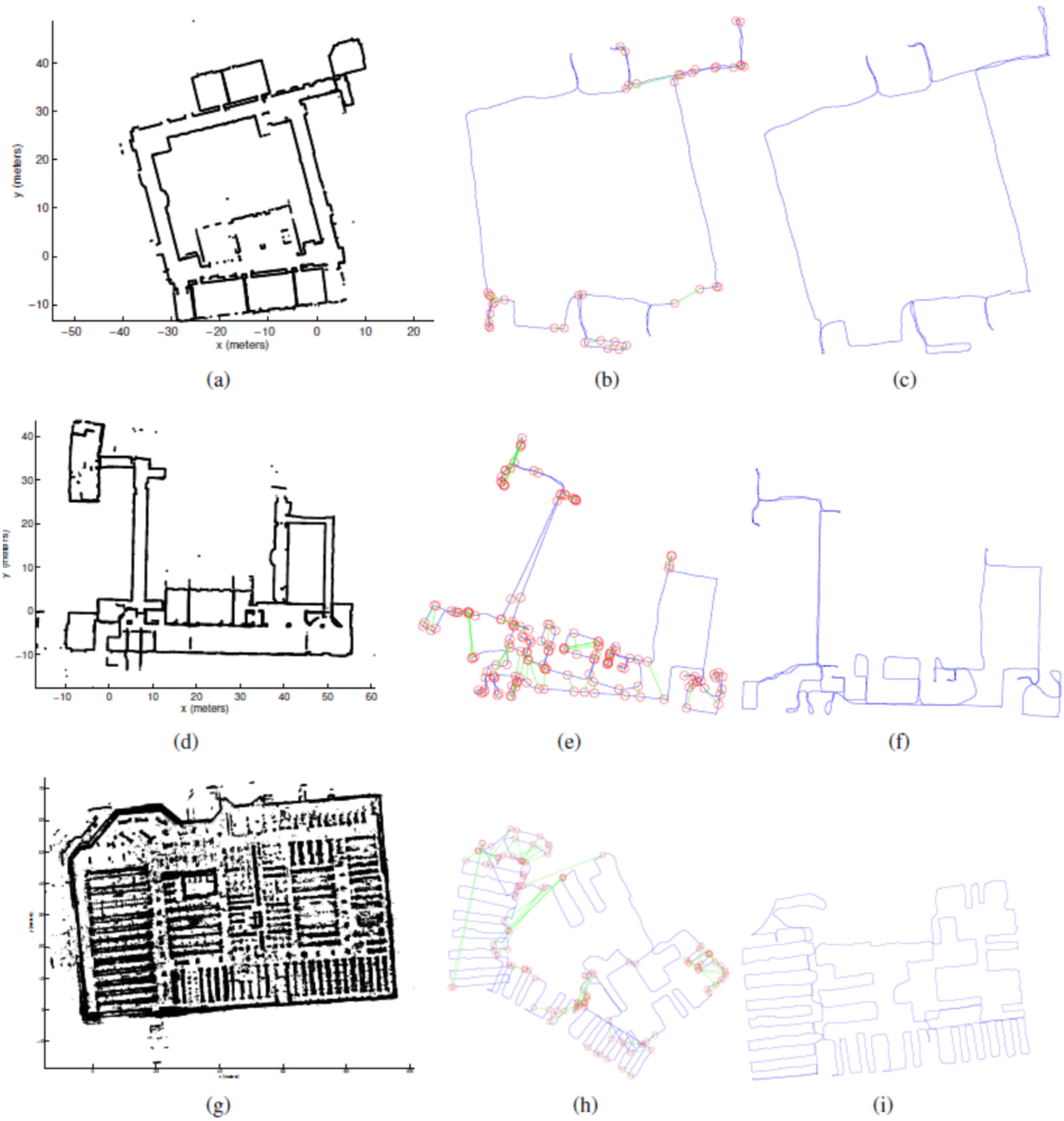
(a) (b)

Figure 8: Example scan of equipment in hospital's hybrid operating room: (a) picture of scanned area; (b) object model triangulation of operating table and equipment.

1.2 Loop closure transformation estimation and validation

In many simultaneous localization and mapping (SLAM) systems, it is desirable to exploit the fact that the system is traversing though a previously visited environment. Once these locations, commonly known as loop closures, have been detected the system must be able to both compute and verify the relative transformation between proposed locations. In this paper we present two independent algorithms, using 2D LiDAR scanners, for robustly computing the transformation between arbitrary locations with overlapping geometry and validating the resulting transforms. First, a scan matching algorithm based on a genetic search and a fractional distance metric is presented. Secondly, two metrics are proposed to verify the recovered transforms. Through experimental results the proposed algorithms are shown to robustly estimate and validate loop closure transformations for both manually and automatically defined candidates.

Figure 17. Results of applying the end-to-end system. (a),(d),(e) The occupancy grid maps that result from the RBPF algorithm. (b),(e),(h) The dead reckoning trajectories with validated loop closure constraints overlain. (c),(f),(i) The 3D paths viewed from the top down after optimization has been applied.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

1.3 Simplified Floor Plan Modeling and Room Labeling [3]

Automatic generation of building floor plans is useful in many emerging applications, including indoor navigation, augmented and virtual reality, as well as building energy simulation software. These applications require watertight models with limited complexity. In this paper, we present an approach that produces 2.5D extruded watertight models of building interiors from either 2D particle filter grid maps or full 3D point-clouds captured by mobile mapping systems. Our approach is to triangulate a 2D sampling of wall positions and separate these triangles into interior and exterior sets. We partition the interior volume of the building model by rooms, then simplify the model to reduce noise. Such labels are useful for building energy simulations involving thermal models, as well as for ensuring geometric accuracy of the resulting 3D model. We experimentally verify the performance of our proposed approach on a wide variety of buildings. Our approach is efficient enough to be used in real-time in conjunction with Simultaneous Localization and Mapping (SLAM) applications. Examples of this approach are shown in the figures below.

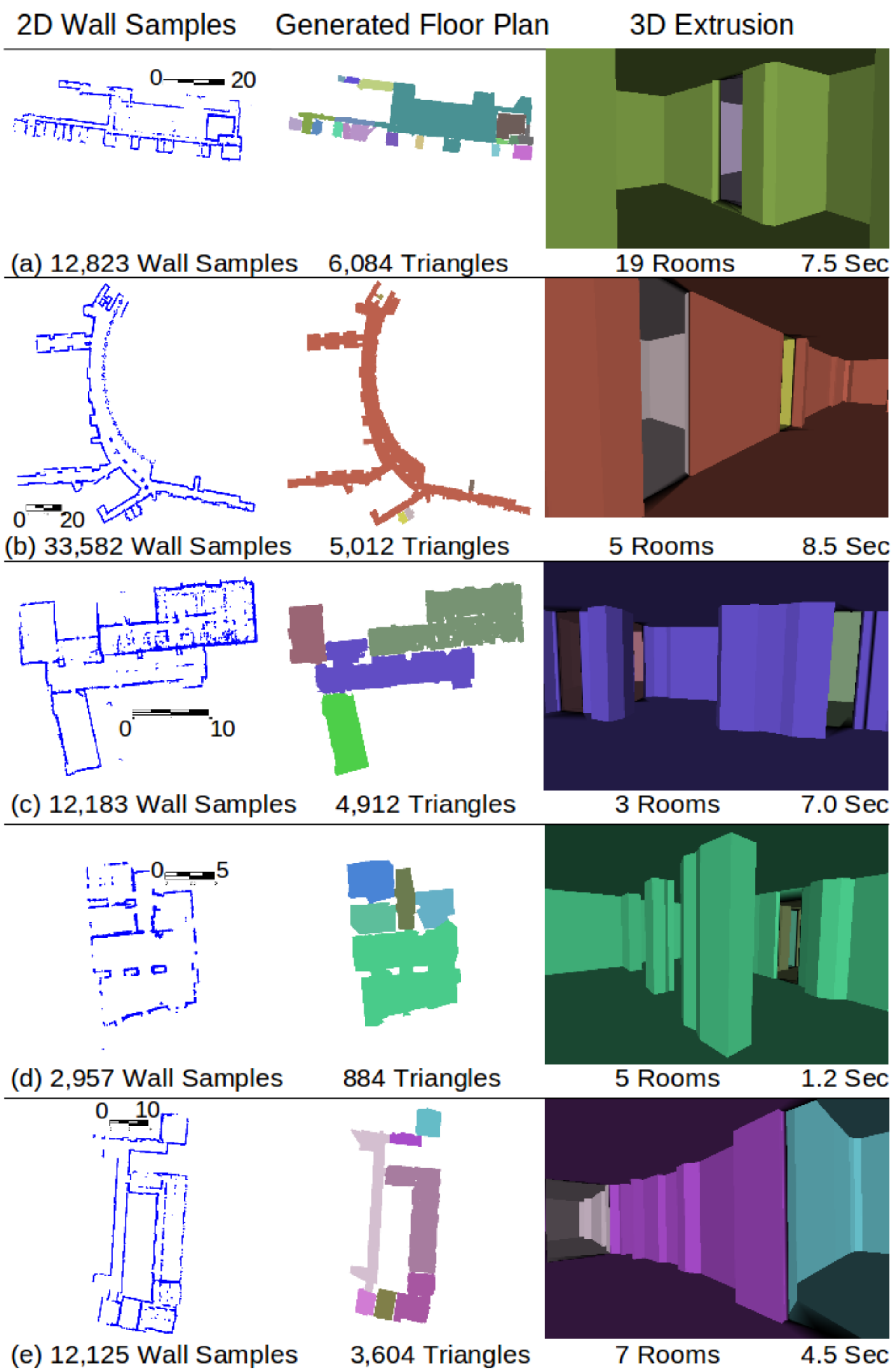


Figure 2: Floor plan construction from estimated position of wall samples. Left column indicates wall samples, middle column indicates generated 2D floor plan, and right column indicates 3D extrusion of building model from floor plan. (a) Mid-sized cubicle area, (b) hotel

lobby and hallways, (c) student offices and cubicles, (d) small office complex, (d) academic building hallways and cubicles.

1.4 Floor Plan Generation from 3D point clouds [8]:

We have developed an algorithm that generates as-built architectural floor plans by separating the floors of the Li-DAR scan of a building, selecting a representative sampling of wall scans for each floor, and triangulating these samplings to develop a watertight representation of the walls for each of the scanned areas. Curves and straight line segments are fit to these walls, in order to mitigate any registration errors from the original scans. This method is not dependent on the scanning system and can successfully process noisy scans with non-zero registration error. Most of the processing is performed after a dramatic dimensionality reduction, yielding a scalable approach. We demonstrate the effectiveness of our approach on a three story point cloud from a commercial building as well as on the lobby and hallways of a hotel. An example of the application of this method is shown in the figure below:

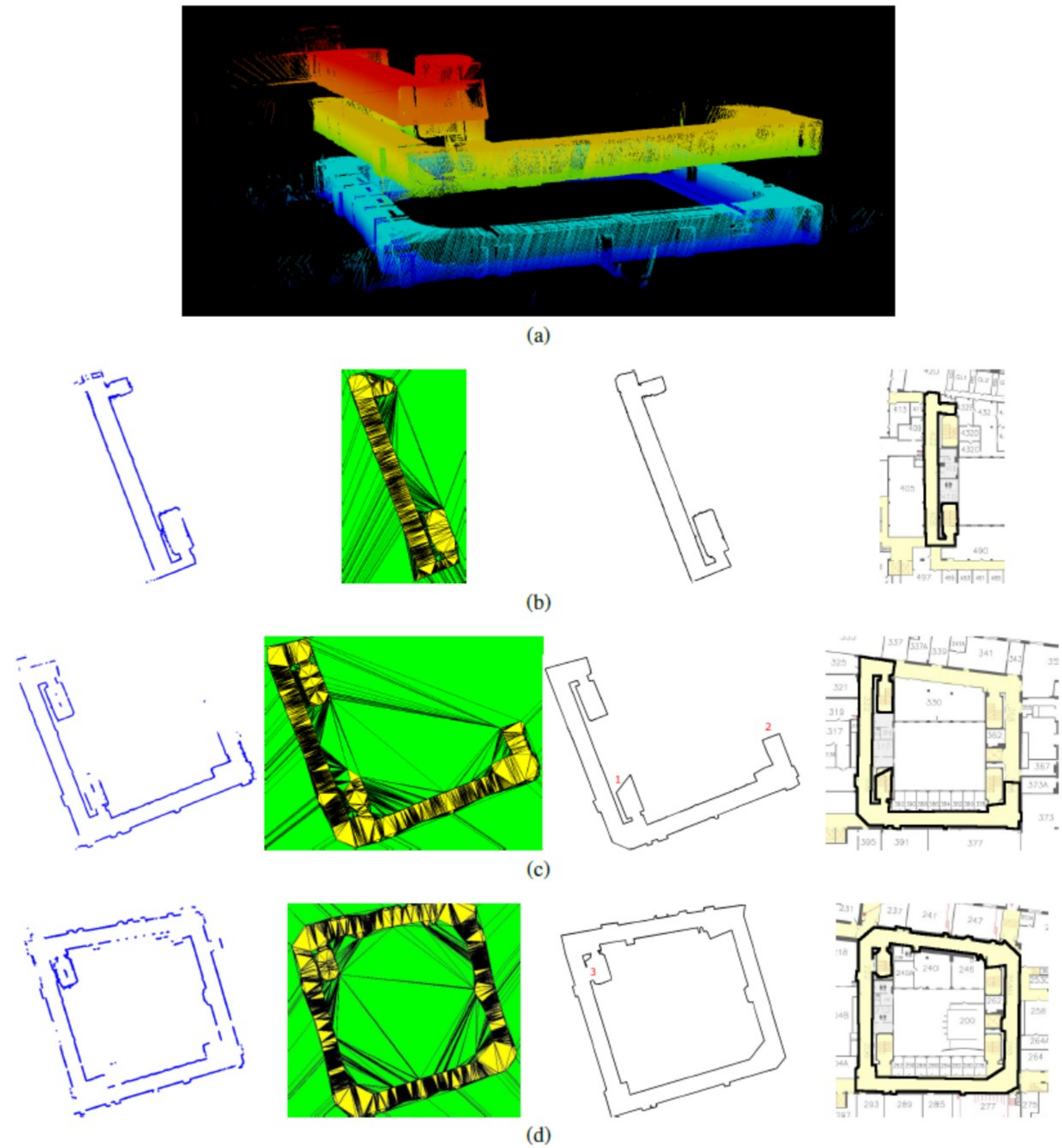


Figure 9. (a) Full point cloud for three-story model, taken with mobile scanning system; (b-d) Processing of each story, with (left to right) wall sample locations, triangulation labeling, watertight curve-fit model, and comparison against ground-truth blueprints.

1.3 Watertight Planar Surface Reconstruction with Voxel Carving [4]

3D modeling of building architecture from point-cloud scans is a rapidly advancing field. These models are used in augmented reality, navigation, and energy simulation applications. State-of-the-art scanning produces accurate pointclouds of building interiors containing hundreds of millions of points. Current surface reconstruction techniques either do not preserve sharp features common in a man-made structures, do not guarantee watertightness, or are not constructed in a scalable manner. We have developed an approach that generates watertight triangulated surfaces from input point-clouds, preserving the sharp features common in buildings. The input point-cloud is converted into a voxelized representation, utilizing a memory-efficient data structure. The triangulation is produced by analyzing planar regions within the model. These regions are represented with an efficient number of elements, while still preserving triangle quality. This approach can be applied to data of arbitrary size to result in detailed models. We apply this technique to several data sets of building interiors and analyze the accuracy of the resulting surfaces with respect to the input point-clouds. An example of this method is shown in the figure below:

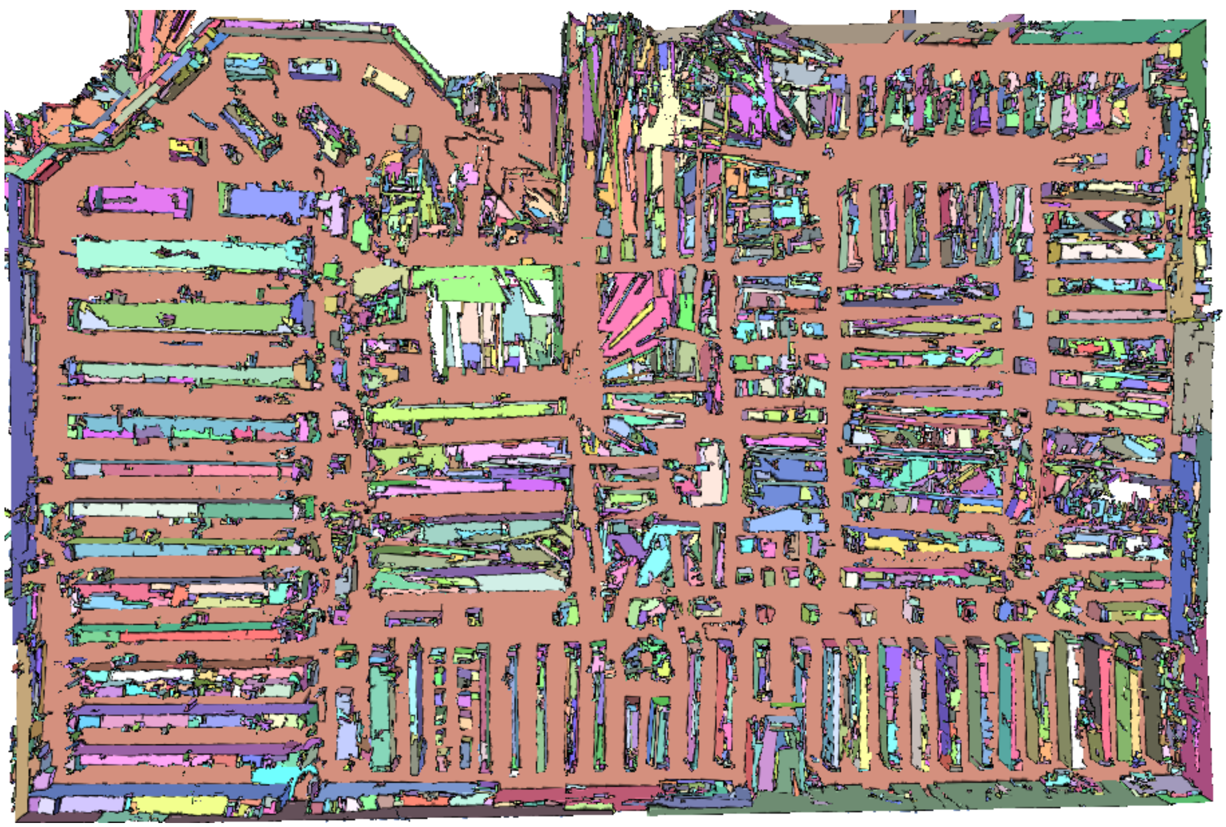


Figure 2: Top-down view of surface reconstruction of a warehouse-sized retail shopping center. Each planar region given a random color. Generated with resolution of 10 cm.

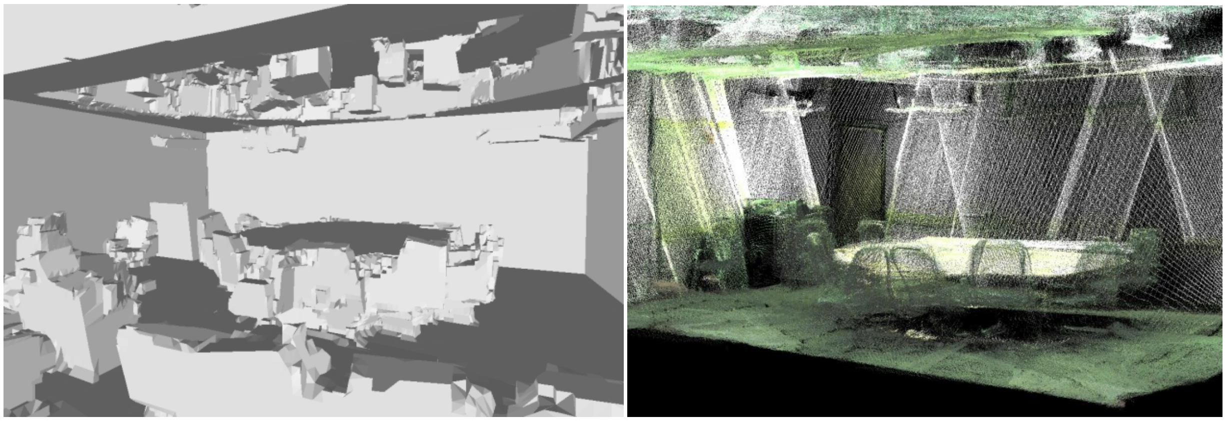


Figure 3: On left, surface reconstruction of a 10.5 m x 9.5 m conference room with table and chairs, at resolution of 5 cm. On right, the input point cloud.

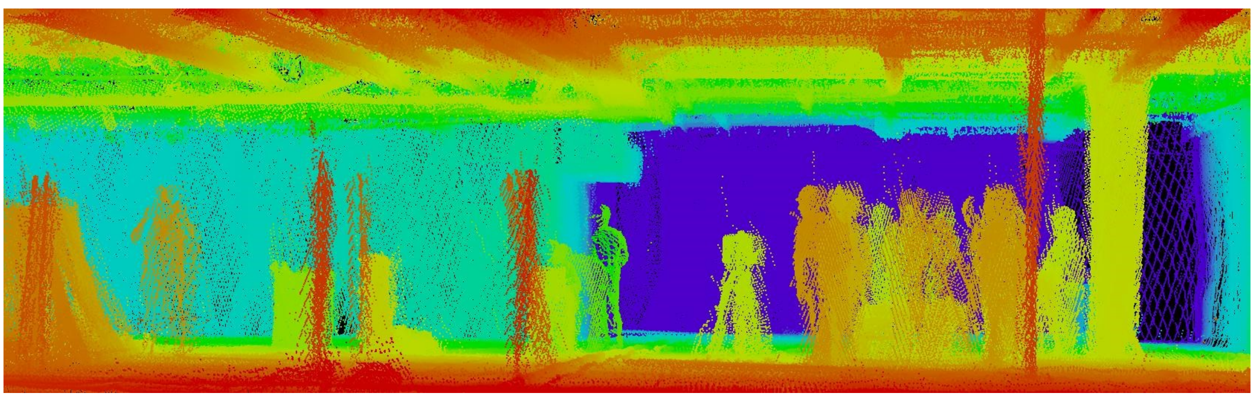


Figure 4 : Input point cloud of construction area, colored by depth from camera

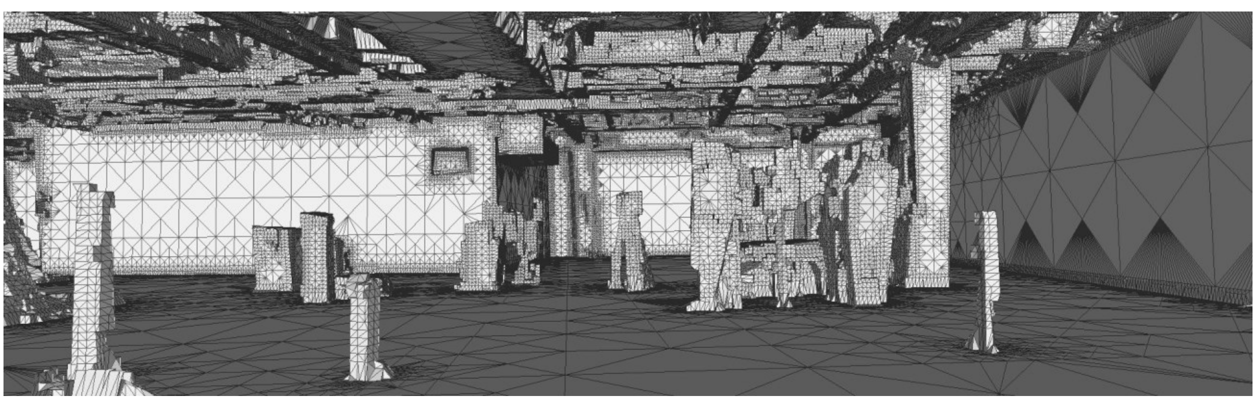


Figure 5: Generated surface reconstruction, showing triangle elements. Resolution: 5 cm.